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The GOODS-North Radio Galaxies: On the Origin of the Radio Emission

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Abstract. We report on a preliminary study concerning the origin of radio emission within radio galaxies at $L(1.4\text{GHz}) > 1\text{E}24$ W/Hz in the GOODS-N field. In the local universe, Condon et al. (1989) and Yun et al. (2001) have shown that in galaxies with radio luminosities greater than 1×10^{23} W/Hz the majority of the radio emission originates from a ‘monster’ i.e., an AGN. Using the Chandra 2Msec X-ray image centered on the GOODS-N field and a reprocessed VLA HDF A-array data plus newly acquired VLA B-array data ($\sigma=5.3\mu\text{Jy}$), we find that radio galaxies (with spectroscopic redshifts; all have $z>1$) with $L(1.4\text{GHz}) > 1\text{E}24$ W/Hz typically have an X-ray detection rate of 72% (60% emit hard X-rays suggesting an AGN origin for the radio emission) in contrast to 25% for radio galaxies with $L < 1 \times 10^{23}$ W/Hz. The ACS images of these $L[1.4\text{GHz}] \geq 1 \times 10^{24}$ W/Hz galaxies typically show compact rather than extended galaxy morphology which is generally found for the less luminous radio emitting galaxies but a few appear to be ongoing galaxy mergers. We also present SED fitting for these luminous radio galaxies including Spitzer IRAC & MIPS 24u photometry and 60% show distinct power-law SED indicative of an AGN. Initial results tell us that the X-ray emitting radio galaxy population are generally not submm sources but the few ($\sim 10\%$) that are SCUBA sources appear to be the small AGN population found by Pope et al. and others.

1. Introduction

Surveys of galaxies at $z > 1$ made from radio to X-ray (e.g., Owen & Morrison 2006, Hasinger et al. 1998, Lilly et al. 1996, Richards et al. 1998) indicate that star-formation (SF) is an essential component in the energetics of galaxies in the early universe. Radio continuum observations have been used as a sensitive, unbiased probe of star-formation (SF) in galaxies to high redshift (e.g., Ivison et al. 2002, Chapman et al. 2003). Using the well-known radio/far-IR correlation (e.g., Dickey & Salpeter 1984, Helou, Soifer & Rowan-Robinson 1985), the radio emission is linked to ongoing SF, which is unaffected by dust obscuration. Radio observations also act as a useful probe of AGN activity, despite any obscuration, through radio morphology (requires sufficiently high resolution), spectral index (α , where $S_\nu \propto \nu^\alpha$), or via anomalously high radio luminosities, $L \geq 1 \times 10^{23}$ W/Hz. However the origin of the radio emission is not always easy to determine from radio observations alone and at higher redshifts this problem becomes more pronounced. To detect the high- z AGN/starburst (SB) population deep radio observations are required and to use the spectral index to classify the radio galaxy population one must observe at more than one frequency. Given

the faintness of the μJy radio sources observing more that more frequency is prohibitive in terms of integration time and because of the negative spectral index at frequency higher than 1.4GHz. In addition, radio resolution (beam=1.5'' at 20cm) at high redshift is not sufficient to resolve the radio morphology thereby yielding an ambiguity regarding the origin of the radio emission. Thus while we know where to look for activity galaxies but do not know which type of activity has been detected.

This preliminary study uses the excellent multi-wavelength data that exist in the GOODS North field to assess the origin of the radio. In the local universe, Condon et al. (2002) and Yun et al. (2001) have shown that in galaxies with radio luminosities greater than $1 \times 10^{23} \text{ W/Hz}$ the majority of the radio emission originates from a ‘monster’ i.e., an AGN. Using the Chandra 2Msec X-ray image centered on the GOODS-N field and a reprocessed VLA HDF A-array data plus newly acquired VLA B-array data (rms=5.3 μJy), we determine which of the $L(1.4\text{GHz}) > 1\text{E}24 \text{ W/Hz}$ radio galaxies are hard X-ray sources the signature of an AGN.

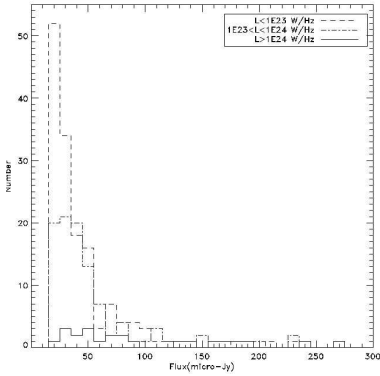


Figure 1. Histogram of radio fluxes separated into different radio luminosity classes using spectroscopic redshifts

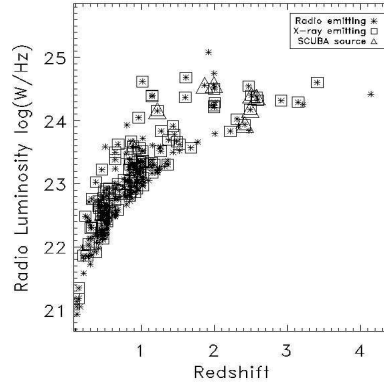


Figure 2. Radio luminosity as a function of redshift. 2 Msec Chandra X-ray detections are denoted by squares and Scuba detection by triangles.

2. Data

The X-ray data used in this analysis are from the ultra-deep Chandra 2Msec survey centered on the GOODS-N field. This survey resolves the bulk of the 0.5-8.0 keV background, providing the deepest view of the universe at this band (Alexander et al. 2003). The galaxian types detected in this survey are absorbed and unabsorbed AGN-types and starburst galaxies in decreasing order of source-density. Hard X-rays (2-8 keV) are generally link to AGNs (Bauer et al. 2002) hence provide a method for classifying the power source in radio galaxies. The radio data consists of 40hr of archival VLA A-array (Richards 2000) and 28hr of new VLA B-array data centered on the GOODS-N field. AIPS reprocessing of the archival data plus the addition of the new VLA data has yielded a

rms $\sim 5.3\mu\text{Jy}$ in the phase center of the map. A 4σ radio sources catalog was constructed using the AIPS task SAD while the residual SAD image was inspected for missed sources. Details can be found in Morrison et al. (2007). Further VLA observations by Morrison et al. will total 150hr in A+B+C+D arrays yielding a map with an estimated rms $\sim 3\mu\text{Jy}$. These data will be published in a future paper. MIR & FIR data were obtained from the Spitzer Legacy project GOODS dataset which have obtained the deepest observations with that telescope at 3.6-24 μm using IRAC and MIPS science detectors. All radio galaxies in this study have measured redshifts obtained from the literature. Information on the ground-base optical/NIR & HST-ACS data can be found in Giavalisco et al. 2004. Submm data comes from the GOODS-N super-map (Borys et al. 2003; Pope et al. 2005)

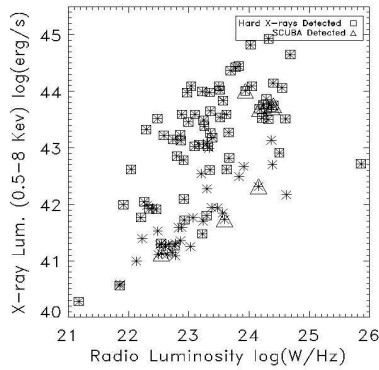


Figure 3. Figure shows the radio luminosity and X-ray luminosity of the 72% radio galaxies which are detected in the 2Msec Chandra data.

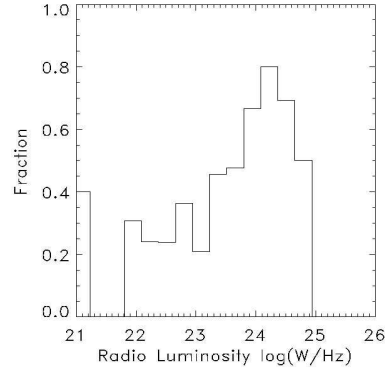


Figure 4. Fraction of radio galaxies emitting X-rays (0.5-8KeV) normalized by the total number of radio galaxies in a particular radio luminosity bin.

3. Results

Figure 1 is histogram of radio fluxes separated into different radio luminosity classes using spectroscopic redshifts. At least 10% of the μJy radio sources are made-up of radio galaxies with $L \geq 1 \times 10^{24}$ W/Hz. Here we consider the $L \geq 1 \times 10^{24}$ W/Hz radio galaxy population. In Figure 2 we see the redshift distribution and the radio luminosity of the galaxies. All radio galaxies in our sample with X-ray emission from 0.2-8.0 keV are label with squares (Alexander et al. 2003) while SCUBA detected galaxies are denoted with a triangle (Pope et al. 2005). At $z \sim 0$, this radio population is made up of mainly AGN's (Yun et al. 2001). The question we ask here is what powers the radio emission at higher redshift: AGN or SB? In Figure 2, 72% of the $L \geq 1 \times 10^{24}$ W/Hz radio galaxies are emitting X-ray and 80% of those are emitting hard (2-8KeV) X-rays (Fig. 3). Thus 60% of all the $L \geq 1 \times 10^{24}$ W/Hz radio galaxies in this sample are powered by an AGN if one assumes that hard X-ray are only produced by AGNs. (However, it is known that many radio galaxies are not X-ray luminous

thus we are missing radio AGNs if we use only the X-ray emission as a tracer of AGNs.) Figure 4, the fraction of radio galaxies emitting X-rays (0.5-8KeV) normalized by the total number of radio galaxies in a particular radio luminosity bin. The fraction varies from 25% for $L < 1 \times 10^{23}$ W/Hz and up to 72% for $L \geq 1 \times 10^{24}$ W/Hz. The turn over appears to be at 1×10^{23} W/Hz the same radio luminosity Condon et al. (2002) and Yun et al. (2001) found for the radio turnover from SB to AGN powered radio emission.

We have done preliminary SED fitting for each galaxy in this sample. A total of 13 photometric data points were used ranging from optical, NIR, MIR, and $24\mu\text{m}$. Out of 29 radio galaxies in this sample with $L \geq 1 \times 10^{24}$ W/Hz, 17 or $\sim 60\%$ have a power-law dominant SED. Many of these galaxies have SED's that follow a power-law from U-band through IRAC & $24\mu\text{m}$ emission indicative of an AGN spectrum. The 2 SED fit uses the Bruzual/Charlot SEDs for the optical/NIR portion of the SED while the MIR part is from Dale & Helou. From Pope et al. (2005) $\sim 10\%$ of the radio emitting SCUBA sources have hard X-ray emission thus these sources appear to be AGNs based on X-ray diagnostics and their power-law SED.

The ACS images of these radio galaxies typically show compact rather than extended galaxy morphology as is generally found for the less luminous radio emitting SB galaxies. A few of these galaxies appear to be ongoing galaxy mergers.

4. Summary

Our $L \geq 1 \times 10^{24}$ W/Hz radio galaxy sample at $z > 1$ has up to an 80% detection rate in X-rays and a 60% detection rate in hard X-rays indicating that for those radio galaxies their radio emission is powered by an AGN. The fraction of detected radio galaxies in X-ray varies from 25% below 1×10^{23} W/Hz to 80% near 2×10^{24} W/Hz. The change in the X-ray detected fraction appears to increase at 1×10^{23} W/Hz the same radio luminosity region where local radio galaxies transition between starburst powered radio emission ($< 1 \times 10^{23}$ W/Hz) and AGN powered radio emission ($\geq 1 \times 10^{23}$ W/Hz). The radio galaxies with SCUBA detections generally appear to be starburst since only a few have any associated hard X-ray emission.

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